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Relationship between the Mass Concentration and Light Attenuation of Particulate Emissions from Coal-Fired Power Plants (Journal Version)

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16. ABSTRACT

Data are presented on 40 mass concentration-light attenuation tests of particulate emissions at coal-fired power plants with electrostatic precipitator controls, and on particle size measurements at two plants near the high and low extremes in the range of the mass concentration-light attenuation tests.

Good correlations were observed between mass concentration and light attenuation measurements at most of the plants during the typically three-day test periods. Ninety three percent of the tests had correlation coefficients of 0.90 or better. Unfortunately, the relationship varied considerable from plant to plant. It varied from a low of 1.14 g/m^2 to a high of 7.70 g/m^2. A theoretical analysis of the light attenuation to mass concentration ratio from the particle size measurements at the plants near the range extremes accounted for about half of the measured range.

The repeatability of several mass concentration-light attenuation tests at the same plants at different times was inconsistent; however, these tests indicated that more accurate monitoring of the mass concentration of particulate emissions by the plant's opacity monitoring transmissometer is obtained if an empirically established mass concentration-light attenuation relationship is used to calibrate the transmissometer for the plant.

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Relationship between the Mass Concentration and Light Attenuation of Particulate Emissions from Coal-Fired Power Plants

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Data are presented on 40 mass concentration-light attenuation tests of particulate emissions at coal-fired power plants with electrostatic precipitator controls, and on particle size measurements at two plants near the high and low extremes in the range of the mass concentration-light attenuation ratio. Good correlations were observed between mass concentration and light attenuation measurements at most of the plants during the typically three-day test periods. Ninety-three percent of the tests had correlation coefficients of 0.90 or better. Unfortunately, the relationship varied considerably from plant to plant. It varied from a low of 1.14 g/m^2 to a high of 7.70 g/m^2. A calculation of the light attenuation to mass concentration ratio from the measured particle size distributions at the two plants near the high/low ratio extremes indicated that particle size differences could account for about half of the measured range. The repeatability of the mass concentration-light attenuation tests at the same plants at different times was inconsistent. However, these tests indicated that more accurate monitoring of the mass concentration of particulate emissions could be obtained with a plant's opacity monitoring transmissometer if an empirically established mass concentration–light attenuation relationship is used to calibrate the transmissometer for the plant.

The U.S. Environmental Protection Agency requires continuous opacity monitors (COMs) on all fossil fuel-fired plants constructed after 1971, and many states require COMs on older plants. Currently, transmissometers are used to monitor the opacity (1 − transmittance) of the particulate emissions, which, along with the mass standard, is a separately enforceable emission standard. The opacity standards are beneficial for three reasons: (1) they provide a simple indication of particulate emission control performance, (2) they are readily measured by a trained smoke observer, and (3) they are easily monitored by in-stack transmissometers; consequently, they permit plant operators and air pollution control agencies to maintain cost-effective surveillance of the performance of particulate emission control equipment. Although mass and opacity emission standards are separately enforceable, the opacity standard is usually subservient to the mass standard in cases of conflict.[1]

Since transmissometers are well established as reliable emission monitors and are already installed in a large number of plants for particulate opacity monitoring, their applicability to particulate concentration monitoring has received considerable attention. Much of this attention has been given to coal-fired plants with electrostatic precipitator (ESP) particulate emission controls. Some of this information has been published[2-5]; however, much of the data is found in unpublished technical reports and personal files and are not easily obtained. Unfortunately, the data often lack the necessary detail for light attenuation-mass concentration intercomparison. For example, the light attenuation data are often presented as opacity readings with no indication of measurement pathlength and/or the mass measurements are presented as emission rates without stack/duct size and velocity data. Such presentations do not permit the necessary normalization of data for intercomparison.

This paper includes mass concentration–light attenuation data that were collected at a 100-MW coal-fired power plant in the Midwest (Plant A), contrasting data (published earlier[4]) that were obtained at a different coal-fired power plant in the East (Plant B), and particle size data for both plants. In addition, other published and unpublished data are reviewed to assist in establishing the quality and range of observed mass concentration–light attenuation correlations.

Data Sources and Test Procedures

Plant A had ESP emission control and burned pulverized coal with a sulfur content around 4 percent. Sampling of the effluent was conducted in a 5.1 × 1.6-m rectangular duct between the ESP outlet and the induced draft (ID) fan. At the sampling site the duct was oriented vertically and the effluent flowed downward. Twelve 7.6-cm diameter ports were equally spaced across the 5.1-m dimension of the duct for traverse sampling. However, for this study, only one of these ports near the center of the duct was used for the mass concentration measurements. Another slightly larger 10.2-cm diameter port was installed near the center of the duct approximately 1.5 m above and upstream of the mass sampling port for the transmissometer light attenuation measurements. Figure 1 is a schematic of the sampling site.

The EPA Method 5 procedure described in the *Federal Register* for measuring particulate emissions from stationary sources was followed.[6] All procedures were conducted except Method 5 traverse of the duct; instead, only a three-point traverse across the duct at the one port in the center of the duct near the transmissometer was made since only the mass concentration at the transmissometer was sought.

The light attenuation was measured with a Lear Siegler RM41P portable transmissometer, which met the *Federal Register* design specifications for opacity monitoring trans-

missometers.[7] The zero and span of the transmissometer was set with the probe at effluent temperature at the beginning of each mass concentration measurement and verified at the end of each measurement. Detailed information about the transmissometer can be found in the manufacturer's operation manual.[8] The high data points at plant A were obtained by reducing the efficiency of the plant's ESP particulate control equipment. The ESP efficiency was reduced by cutting electrical power to sections of the ESPs.

The data for Plant B were obtained at a small 135-MW coal-fired power plant in the Southeast. The plant had ESP emission control and burned pulverized coal with a sulfur content around 1 percent. Sampling of the effluent was conducted in a 3-m diameter steel stack on the roof of the plant. All measurements were made through three 10.2-cm diameter sampling ports located at the base of the stack 1.5 m above the roof. The ports were approximately 10 m downstream of the ID fan and 50 m downstream of the ESPs. Figure 2 is a schematic of the sampling site.

At this plant, the Method 5 procedure was also used for measuring the particulate emissions. As with Plant A, all of the procedures were followed except for transverse difference. Here, the stack was traversed, but the number of traverse points was reduced to 16 from the 48 required by Method 5. At this source, similar results were observed when 48- and 16-point traverse measurements were compared. The light attenuation measurements were made with the same Lear Siegler RM41P transmissometer used for Plant A. More information about this test site with additional light attenuation–mass concentration tests is available.[4] As with Plant A, high data points for Plant B were obtained by reducing the efficiency of the plant's ESP particulate control equipment.

In addition to these two tests, 38 other mass concentration–light attenuation tests at coal-fired power plants with

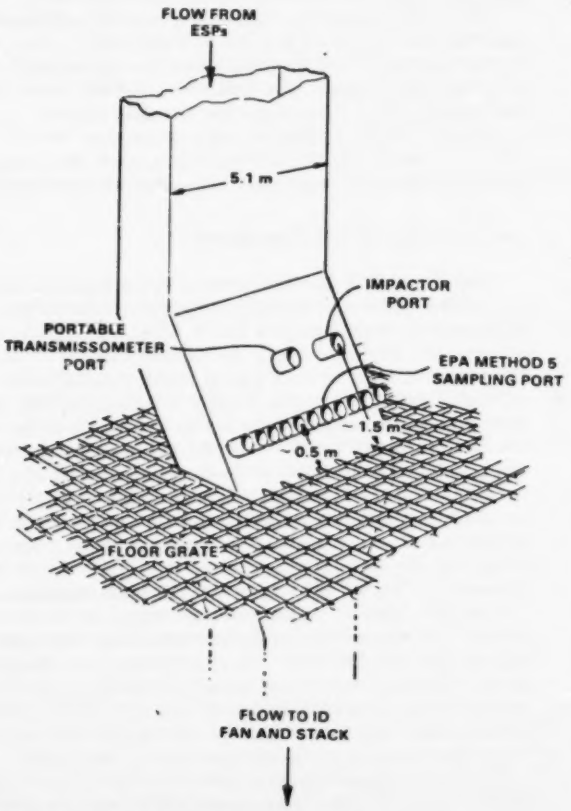

Figure 1. Schematic of sampling site at Plant A.

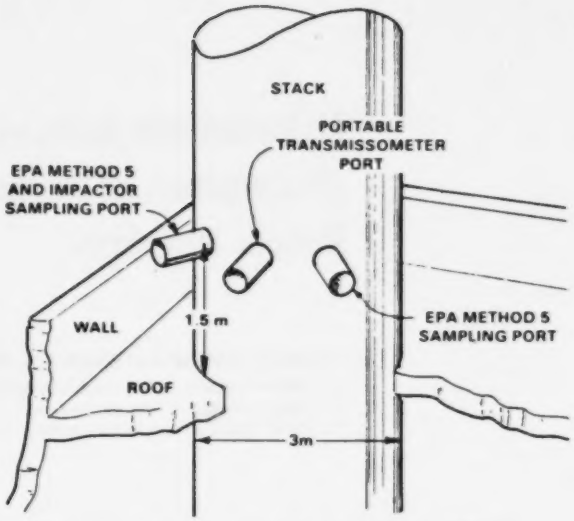

Figure 2. Schematic of sampling site at Plant B.

ESP emission controls were reviewed. In reviewing the data, several arbitrary selection criteria were used:

(1) Only tests with eight or more measurements over consecutive two-to-three day periods were reviewed;

(2) No mass concentration measurements greater than 0.8 g/m^3 or light attenuation measurements greater than 0.25 m^{-1} were used; and

(3) The range of measurements during a test had to exceed 8 to 1 for the light attenuation coefficient and/or the mass concentration measurements.

Criterion (1) was set to insure enough test data for confident regression analyses. Eight measurements generally require about three days of sampling when EPA Method 5 is used to collect the particle samples. Criterion (2) was used for preventing data with unrealistic particle and attenuation characteristics from affecting the test observations. For example, increasing particle concentrations by defeating ESP capacity generally increases emission particle size; consequently, the cap on the upper concentration range of the data was expected to eliminate data for which the particle size increased unrealistically above what might be expected during normal loss of ESP collecting efficiency. The cap on the light attenuation coefficient was established to eliminate data affected by multiple light scattering; however, this value is very arbitrary since multiple scattering will also depend on particle characteristics and effluent depth. For an effluent depth of 5 m (average for coal-fired power plants), an attenuation coefficient of 0.25 m^{-1} corresponds to an opacity of 71 percent. Criterion (3) was set to insure enough range in test data for confident regression analyses. Without a sufficient range of measurements, regression analyses results would be too controlled by the precision of the measurement methods.

Particle Size Tests

The sizes of the particles emitted by coal-fired power plants A and B were measured by size selective sampling with a Unversity of Washington Mark III source test cascade impactor. The Mark III impactor consists of seven impactor stages (and backup filter) with size cuts ranging from around 0.25- to 20-μm diameter. The actual size cuts depend on the sampling rate and particle density. The impaction surfaces were 1 to 2-mil stainless steel shim stock coated with Apiezon L to improve particle adhesion.[9] The Apiezon L coating was used because it has been found weight stable for this impactor at the temperatures of the effluents of both plants

Table I. Tests of mass concentration and light attenuation of particulate emissions from coal-fired power plants with ESP controls.

Test No./Ref.	Number of measurements	Range of measurements: Attenuation (σ), (m^{-1})	Range of measurements: Concentration[c] (C), (g/m^3)	C vs σ linear regression line: Slope (g/m^2)	C vs σ linear regression line: Intercept (g/m^3)	C vs σ correlation coefficient	Standard error of estimate (g/m^3)
1/A[a]	10	0.012–0.113	0.081–0.798	6.27	0.056	0.97	0.071
2/4	16	0.013–0.150	0.039–0.486	2.44	0.012	0.96	0.034
3/4,B[b]	9	0.015–0.246	0.055–0.441	1.56	0.006	0.96	0.043
4/5	11	0.025–0.163	0.031–0.585	3.62	−0.014	0.85	0.092
5/5	11	0.018–0.093	0.023–0.273	2.64	0.004	0.85	0.045
6/5	11	0.030–0.116	0.060–0.569	5.88	−0.121	0.95	0.057
7/5	9	0.019–0.092	0.015–0.363	4.65	−0.087	0.98	0.021
8/5	11	0.006–0.067	0.017–0.189	2.62	0.019	0.94	0.019
9/5	11	0.005–0.078	0.025–0.275	2.69	0.027	0.97	0.023
10/5	8	0.014–0.096	0.013–0.195	2.32	−0.007	0.95	0.026
11/5	8	0.014–0.141	0.032–0.292	1.65	0.038	0.97	0.024
12/5	11	0.012–0.099	0.019–0.306	2.75	−0.020	0.95	0.031
13/5	10	0.004–0.112	0.033–0.282	2.50	0.016	0.93	0.036
14/5	11	0.037–0.166	0.025–0.279	2.04	−0.025	0.94	0.034
15/5	9	0.002–0.124	0.024–0.511	4.28	−0.011	1.00	0.014
16/5	11	0.002–0.116	0.011–0.658	4.30	−0.024	0.91	0.085
17/5	11	0.005–0.075	0.010–0.282	3.47	0.006	0.99	0.009
18/5	9	0.023–0.083	0.063–0.527	7.70	−0.095	1.00	0.016
19/5	8	0.026–0.069	0.033–0.341	7.11	−0.148	0.98	0.022
20/5	9	0.002–0.071	0.015–0.416	5.36	−0.003	0.99	0.022
21/5	11	0.014–0.081	0.057–0.576	5.50	0.035	0.93	0.065
22/5	10	0.018–0.091	0.044–0.501	6.71	−0.066	0.93	0.073
23/5	11	0.005–0.090	0.023–0.343	4.05	0.002	0.99	0.018
24/11	11	0.002–0.201	0.008–0.537	2.50	0.008	0.99	0.023
25/11	10	0.008–0.112	0.008–0.222	2.12	−0.006	0.98	0.016
26/11	10	0.023–0.206	0.019–0.602	2.13	−0.020	0.90	0.084
27/11	11	0.006–0.098	0.031–0.704	7.28	−0.060	0.97	0.059
28/11	14	0.030–0.150	0.012–0.152	1.14	−0.027	0.98	0.011
29/12	8	0.023–0.222	0.021–0.439	2.05	−0.042	0.99	0.026
30/12	8	0.027–0.227	0.039–0.502	2.14	−0.009	0.98	0.037
31/12	8	0.005–0.092	0.032–0.282	3.00	−0.009	0.99	0.020
32/12	9	0.059–0.160	0.039–0.386	3.13	−0.172	0.99	0.021
33/12	9	0.018–0.194	0.039–0.570	2.81	−0.019	0.99	0.028
34/12	8	0.026–0.223	0.086–0.686	2.93	0.017	1.00	0.017
35/12	8	0.006–0.149	0.029–0.490	2.77	0.021	0.96	0.047
36/12	8	0.033–0.204	0.066–0.624	3.20	−0.046	1.00	0.013
37/12	9	0.029–0.243	0.037–0.570	1.85	−0.012	0.86	0.105
38/12	9	0.016–0.164	0.025–0.394	2.45	−0.014	0.99	0.027
39/12	9	0.016–0.196	0.028–0.457	2.23	−0.009	1.00	0.107
40/12	8	0.340–0.230	0.047–0.720	3.17	−0.071	0.98	0.057

[a] Plant A test.
[b] Plant B test.
[c] Actual conditions.

which were approximately 157°C (315°F). The impactor backup filter was glass fiber. At Plants A and B, the size selective samples were collected in the duct and the stack at points that were approximately 1.0 to 0.5 m to the side of the transmissometers, respectively (Figures 1 and 2). The general operating procedures for the impactor can be found in the manufacturer's literature[10] and in a report by Pilat *et al.*[11] The operating procedures recommended by the manufacturer were followed during the study.

Results and Discussion

A summary of the mass concentration–light attenuation measurements of coal-fired power plant emissions with ESP controls that were measured or reviewed for this report is presented in Table I. Examination of the data reveals two obvious results: (1) Good correlations were observed between light attenuation and mass concentration of the emissions during the approximately three day test periods. Seventy-five percent of the correlation coefficients were 0.95 or better, 93 percent were 0.90 or better and all were 0.85 or better. The standard error of the mass concentration estimate averaged 0.037 g/m^3 and was less than 0.092 g/m^3 95 percent of the time. (2) The relationship between the mass concentration and light attenuation varied considerably from plant to plant, and the variation appeared to be random. Slopes of linear regression lines of the mass concentration versus light attenuation coefficient data ranged from a low of 1.14 g/m^2 to a high of 7.70 g/m^2. The average slope was 3.5 g/m^2 and 95 percent of the test results were in the range 4.4 ± 2.9 g/m^2.

In addition to the between-plant observation, several observations can be made from the data on the stability of the mass concentration-light attenuation relationship at individual plants. Some of the tests have been made at the same plant at different times. Tests 2, 3, and 31 were conducted at the same stack and the time between tests was several years. In addition to the multiple tests at this plant, four dual sets of measurements separated by approximately one year were made at other plants. These test sets are 8 and 9, 15 and 16, 20 and 21, and 22 and 23.

A summary of the consistency between these multiple tests is presented in Table II. The table shows that repeat error of the tests at the same plant ranged from 0.5 to 92 percent with an average of 28 percent. The time periods between tests ranged from 10 to 69 months and showed no apparent relation to the repeat error. Although the repeatability at the same plant was inconsistent and sometimes

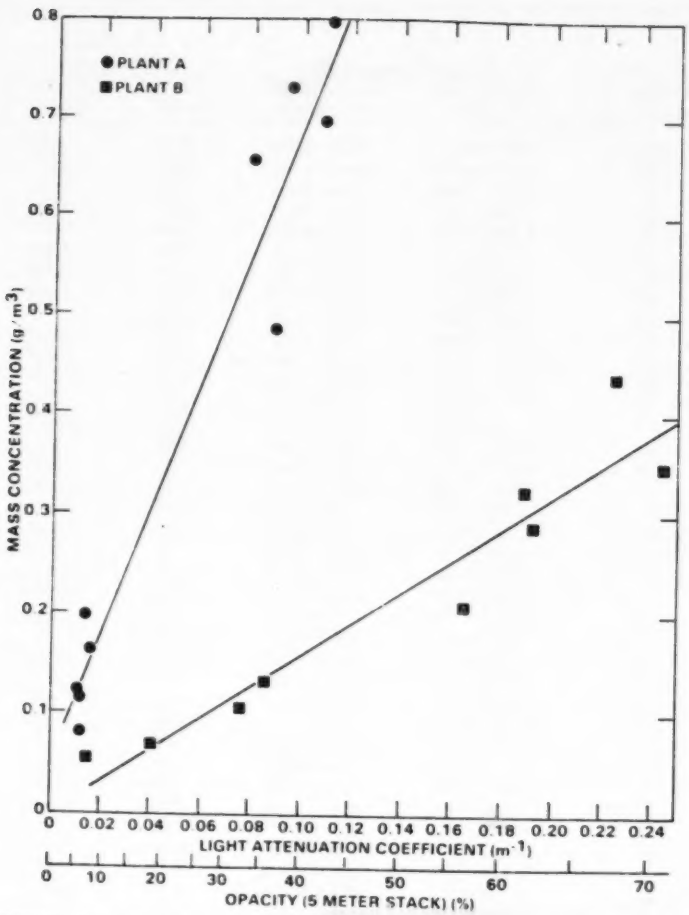

Figure 3. Mass concentration versus light attenuation of particulate emissions at coal-fired power plants with ESP controls.

high, much higher between-plant differences were observed (Table I). The between-plant differences ranged as high as 148 percent. Comparative curves of repeat tests at a coal-fired power plant are shown in Reference 4.

Many possible reasons for the observed differences between the mass concentration and light attenuation of emissions exist, but one of the major reasons for expecting differences is the difference in particle size distributions. The particle size effect on the measurement of particulate emissions by transmissometer has been discussed in several previous publications.[14-16,19]

The particle size measurements made at Plants A and B indicated a difference in particle size distribution between the plants. Figure 4 shows typical cumulative curves of the size selective samples that were collected at the plants. In reducing the data, a particle density of 2.5 g/mL was assumed, after Smith and McCain.[16] The samples were collected from effluents with similar mass concentrations of approximately 0.4 g/m^3, which were obtained by a slight reduction in the ESP control equipment performance. The figure indicates that the mass median diameter of the particulate emissions was about 7.5 μm for Plant A and 3.5 μm for Plant B. The larger particle size and higher mass concentration to light attenuation ratio of Plant A relative to Plant B were consistent with expectations for visible light attenuation by particles in these size ranges.

Additional particle size sampling at Plants A and B showed that the curves in Figure 4 are typical for the Plants. At Plant A, size selective samples obtained at high concentrations (around 1 g/m^3) showed similar results, while measurements at higher concentrations (around 5 g/m^3) showed higher mass median diameters (15 μm). All particle size tests at Plant A were made at the location indicated above and shown in Figure 1. Extensive particle size testing at Plant B,[4] at various locations across the stack, has shown that the curve for Plant B is typical for the plant when ESP efficiency was reduced.

These particle size distributions were used to make theoretical calculation of the light attenuation to mass concentration ratio of Plants A and B. To do this, the incremental size component method described by Thielke and Pilat[18]

Table II. Repeat error of mass concentration-light attenuation tests made at different times at the same coal-fired power plants.

Plant	Test numbers[a]	Time between test (months)	Test repeat error (percent)[b]
A	2–3	38	36
A	2–31	69	23
A	3–31	31	92
C	8–9	10	2.7
D	15–16	12	0.5
E	20–21	11	2.6
F	22–23	12	40

[a] Test numbers same as Table I.
[b] Test repeat error = |slope of first test − slope of second test|/slope of first test.

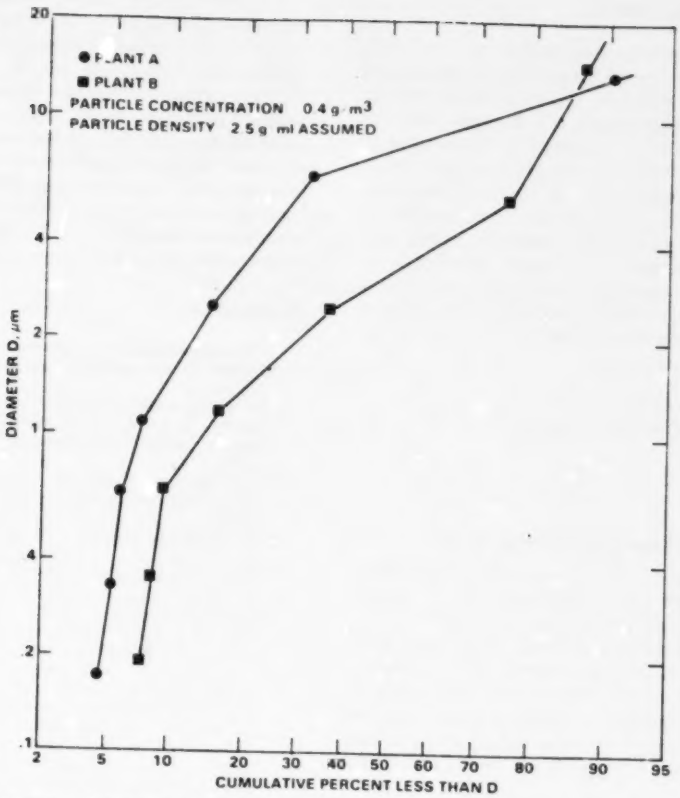

Figure 4. Typical particle size distributions of emissions from coal-fired power plants A and B with small ESP reduction.

was used. Their procedure involves using the impactor size data to break the size distribution into a series of relatively narrow size ranges, using a theoretical particle scattering-size curve to determine the amount of light attenuated by the mass in each size range, and summing up the size increment results to determine the light attenuation to mass concentration ratio of the whole aerosol. In addition to the size distributions, the calculations require particle density and refractive index inputs. Since they were not measured, a density of 2.5 g/mL was assumed as for the impactor data reduction, and the particle composition was assumed to be similar to SiO_2 with a refractive index of 1.5. The theoretical specific concentration to attenuation ratio-particle size curve of Thielke and Pilat for monodisperse spherical particles with refractive index 1.5 was used to obtain the amount of scatter for the size increments. The results of the calculations are shown in Table III.

The calculated light attenuation to mass concentration ratios were 0.295 and 0.556 m^2/g for Plants A and B, respectively. These results compare to measured values of 0.151 and 0.587 m^2/g for Plants A and B respectively. This gives a difference between calculated and measured values of 65 percent for Plant A and 5.4 percent for Plant B. The reason for the large difference at Plant A is not evident from this work. However, the higher calculated result suggests that the problem may be due to measuring the particle size and/or assuming the particle density of Plant A too low. Since the assumed density of 2.5 g/mL seems sufficiently high when compared to the values used by other researchers, a low particle size measurement is more likely. Low particle size measurement would occur if particle reentrainment (particle bounce) occurred in the impactors during sampling. The 5.4 percent difference at Plant B is probably as close as can be expected.

Table III. Calculated light attenuation to mass concentration ratios of coal-fired power plants A and B.

Particle diameter range of size interval (μm)	Mean radius of interval (μm)	Mass fraction in interval		Specific conc. to atten. ratio (cm^3/m^2)	Atten. to mass conc. ratio of interval (m^2/g)	
		A	B	A and B	A	B
<0.13	0.05	0.04	0.07	2.5	0.006	0.001
0.13–0.25	0.09	0.01	0.01	0.52	0.008	0.008
0.25–0.50	0.18	0.01	0.01	0.11	0.036	0.036
0.50–1.0	0.35	0.01	0.05	0.11	0.036	0.182
1.0–2.0	0.71	0.06	0.16	0.50	0.048	0.128
2.0–4.0	1.41	0.10	0.33	0.90	0.044	0.147
4.0–8.0	2.83	0.32	0.19	1.8	0.071	0.042
8.0–16	5.66	0.41	0.06	3.7	0.044	0.006
>16	11.31	0.04	0.12	7.5	0.002	0.006
Totals		1.0	1.0		0.295	0.556

Conclusions and Recommendations

These data indicate that very good mass concentration-light attenuation coefficient relationships can be generated at coal-fired power plants with ESP controls during two- to three-day test periods. Unfortunately, the data also indicate that these relationships change significantly from plant to plant and to a lesser extent with time at a given plant. It can also be concluded from these tests that a transmissometer installed for monitoring the opacity of particulate emissions will also monitor (without site specific calibration) the mass concentration of the particulate emissions, provided the large error (around 66 percent) is acceptable. This will result if the following relationship between the mass concentration and light attenuation coefficient is used:

$$C = 4.4\sigma$$

where: C = mass concentration, g/m^3

σ = light attenuation coefficient, m^{-1}

$$= \frac{1}{l} \ln \frac{1}{1-O}$$

O = opacity

l = pathlength of opacity measurement, m

It appears that the large error for assuming this relationship (with no calibration) can be reduced if the transmissometer is experimentally calibrated for the plant; however, the amount of improvement is not clear. When tests were repeated at the same plant after one or two years, the repeat error ranged from good to poor. This inconsistent repeat error result and the small number of repeat test data lead to this error. More repeat tests of the mass concentration-light attenuation of coal-fired power plant emissions should be made.

Particle size measurements of two plants near the extremes of the mass concentration-light attenuation relationships showed distinct size differences. With the ESP controls slightly reduced to increase emission levels to around 0.4 g/m^3, the mass median diameters of their emissions were measured at approximately 8 μm for the low attenuation-to-mass plant (Plant A) and 4 μm for the high attenuation-to-mass plant (Plant B).

These particle size measurements were used to make theoretical calculations of the light attenuation to mass concentration ratios of the emissions. The calculated light attenuation to mass concentration ratios was higher than the transmissometer measured value by a factor of about two for Plant A and similar for Plant B. The high ratio of light attenuation to mass concentration at Plant A may be due to the use of particle sizes that are too small in the calculation. Particle bounce and reentrainment at the stages of the impactor particle size sampler during measurement would result in erroneously small size measurements. However, other factors such as an unusually high practice density could cause this high calculation and are not eliminated by this study. More tests to characterize the particles of coal-fired power plant emissions that have contrasting scattering characteristics are needed.

In addition to the above recommendations for more repeat tests at the same plants and more characterization tests at plants with contrasting light attenuation–mass concentration relationships, the following recommendations are made:

This paper used the procedure of reducing the performance of ESPs of a plant to create a data range for regression analysis. The procedure causes some increase in particle size and assumes the size increase is representative of plant conditions that cause increased emissions. Data for other conditions that may cause increased emissions should be obtained; for example, burning coal with an ash content higher than the plant's ESPs were designed to control, or using a coal that yields an ash with different electrical resistivity characteristics.

This report evaluates the mass concentration-light attenuation coefficient relationship of plants where the light attenuation coefficient is measured with a visible light transmissometer that meets opacity monitoring specifications. However, evidence indicates that mass concentration–attenuation coefficient relationships may be obtained at other wavelengths that will be less dependent upon the particle characteristics of the emissions; e.g., Uthe describes the use of an infrared transmissometer for the measurement.[17] Theoretical and experimental work on the use of other transmissometer wavelengths and the use of multiwavelength transmissometers should be considered.

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